

Description

AIR AND FUEL SUPPLY SYSTEM FOR COMBUSTION ENGINE

Cross-Reference to Related Application

- [01] This is a continuation of Application No. 10/143,908, filed May 14, 2002, U.S. Patent No. _____, the contents of which are incorporated herein by reference.

Technical Field

- [02] The present invention relates to a combustion engine and, more particularly, to an air and fuel supply system for use with an internal combustion engine.

Background

- [03] An internal combustion engine may include one or more turbochargers for compressing a fluid, which is supplied to one or more combustion chambers within corresponding combustion cylinders. Each turbocharger typically includes a turbine driven by exhaust gases of the engine and a compressor driven by the turbine. The compressor receives the fluid to be compressed and supplies the compressed fluid to the combustion chambers. The fluid compressed by the compressor may be in the form of combustion air or an air/fuel mixture.
- [04] An internal combustion engine may also include a supercharger arranged in series with a turbocharger compressor of an engine. U.S. Patent No. 6,273,076 (Beck et al., issued August 14, 2001) discloses a supercharger having a turbine that drives a compressor to increase the pressure of air flowing to a turbocharger compressor of an engine. In some situations, the air charge temperature may be reduced below ambient air temperature by an early closing of the intake valve.

[05] Early or late closing of the intake valve, referred to as the “Miller Cycle,” may reduce the effective compression ratio of the cylinder, which in turn reduces compression temperature, while maintaining a high expansion ratio. Consequently, a Miller cycle engine may have improved thermal efficiency and reduced exhaust emissions of, for example, oxides of Nitrogen (NO_x). Reduced NO_x emissions are desirable. In a conventional Miller cycle engine, the timing of the intake valve close is typically shifted slightly forward or backward from that of the typical Otto cycle engine. For example, in the Miller cycle engine, the intake valve may remain open until the beginning of the compression stroke.

[06] While a turbocharger may utilize some energy from the engine exhaust, the series supercharger/turbocharger arrangement does not utilize energy from the turbocharger exhaust. Furthermore, the supercharger requires an additional energy source.

[07] The present invention is directed to overcoming one or more of the problems as set forth above.

Summary of the Invention

[08] According to one exemplary aspect of the invention, a method of operating an internal combustion engine, including at least one cylinder and a piston slidable in the cylinder, is provided. The method may include supplying pressurized air from an intake manifold to an air intake port of a combustion chamber in the cylinder, selectively operating an air intake valve to open the air intake port to allow pressurized air to flow between the combustion chamber and the intake manifold substantially during a majority portion of a compression stroke of the piston, and operably controlling a fuel supply system to inject fuel into the combustion chamber after the intake valve is closed.

[09] According to another exemplary aspect of the invention, a variable compression ratio internal combustion engine may include an engine block defining at least one cylinder, a head connected with the engine block, wherein the head includes an air intake port and an exhaust port, and a piston slidable in

each cylinder. A combustion chamber may be defined by the head, the piston, and the cylinder. The engine may include an air intake valve controllably movable to open and close the air intake port, an air supply system including at least one turbocharger fluidly connected to the air intake port, and a fuel supply system operable to controllably inject fuel into the combustion chamber at a selected timing. A variable intake valve closing mechanism may be configured to keep the intake valve open by selective actuation of the variable intake valve closing mechanism.

- [10] According to yet another exemplary aspect of the invention, a method of operating an internal combustion engine, including at least one cylinder and a piston slidable in the cylinder, is provided. The method may include imparting rotational movement to a first turbine and a first compressor of a first turbocharger with exhaust air flowing from an exhaust port of the cylinder, and imparting rotational movement to a second turbine and a second compressor of a second turbocharger with exhaust air flowing from an exhaust duct of the first turbocharger. The method may also include compressing air drawn from atmosphere with the second compressor, compressing air received from the second compressor with the first compressor, and supplying pressurized air from the first compressor to an air intake port of a combustion chamber in the cylinder via an intake manifold. The method also includes controllably operating a fuel supply system to inject fuel directly into the combustion chamber, and selectively operating an air intake valve to open the air intake port to allow pressurized air to flow between the combustion chamber and the intake manifold during a portion of a compression stroke of the piston.

- [11] According to still another exemplary aspect of the invention, a method of controlling an internal combustion engine having a variable compression ratio is provided. The engine may have a block defining a cylinder, a piston slidable in the cylinder, a head connected with the block, and the piston, the cylinder, and the head defining a combustion chamber. The method may

include pressurizing air, supplying the air to an intake manifold, maintaining fluid communication between the combustion chamber and the intake manifold during a portion of an intake stroke and through a predetermined portion of a compression stroke, and supplying a pressurized fuel directly to the combustion chamber during a portion of an combustion stroke.

- [12] It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention.

Brief Description of the Drawings

- [13] The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate several exemplary embodiments of the invention and, together with the description, serve to explain the principles of the invention. In the drawings,
- [14] FIG. 1 is a combination diagrammatic and schematic illustration of an exemplary air supply system for an internal combustion engine in accordance with the invention;
- [15] FIG. 2 is a combination diagrammatic and schematic illustration of an exemplary engine cylinder in accordance with the invention;
- [16] FIG. 3 is a diagrammatic sectional view of the exemplary engine cylinder of FIG. 2;
- [17] FIG. 4 is a graph illustrating an exemplary intake valve actuation as a function of engine crank angle in accordance with the present invention;
- [18] FIG. 5 is a graph illustrating an exemplary fuel injection as a function of engine crank angle in accordance with the present invention;
- [19] FIG. 6 is a combination diagrammatic and schematic illustration of another exemplary air supply system for an internal combustion engine in accordance with the invention; and

[20] FIG. 7 is a combination diagrammatic and schematic illustration of yet another exemplary air supply system for an internal combustion engine in accordance with the invention.

Detailed Description

[21] Reference will now be made in detail to embodiments of the invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

[22] Referring to FIG. 1, an exemplary air supply system 100 for an internal combustion engine 110, for example, a four-stroke, diesel engine, is provided. The internal combustion engine 110 includes an engine block 111 defining a plurality of combustion cylinders 112, the number of which depends upon the particular application. For example, a 4-cylinder engine would include four combustion cylinders, a 6-cylinder engine would include six combustion cylinders, etc. In the exemplary embodiment of FIG. 1, six combustion cylinders 112 are shown. It should be appreciated that the engine 110 may be any other type of internal combustion engine, for example, a gasoline or natural gas engine.

[23] The internal combustion engine 110 also includes an intake manifold 114 and an exhaust manifold 116. The intake manifold 114 provides fluid, for example, air or a fuel/air mixture, to the combustion cylinders 112. The exhaust manifold 116 receives exhaust fluid, for example, exhaust gas, from the combustion cylinders 112. The intake manifold 114 and the exhaust manifold 116 are shown as a single-part construction for simplicity in the drawing. However, it should be appreciated that the intake manifold 114 and/or the exhaust manifold 116 may be constructed as multi-part manifolds, depending upon the particular application.

[24] The air supply system 100 includes a first turbocharger 120 and may include a second turbocharger 140. The first and second turbochargers 120, 140 may be arranged in series with one another such that the second turbocharger

140 provides a first stage of pressurization and the first turbocharger 120 provides a second stage of pressurization. For example, the second turbocharger 140 may be a low pressure turbocharger and the first turbocharger 120 may be a high pressure turbocharger. The first turbocharger 120 includes a turbine 122 and a compressor 124. The turbine 122 is fluidly connected to the exhaust manifold 116 via an exhaust duct 126. The turbine 122 includes a turbine wheel 128 carried by a shaft 130, which in turn may be rotatably carried by a housing 132, for example, a single-part or multi-part housing. The fluid flow path from the exhaust manifold 116 to the turbine 122 may include a variable nozzle (not shown) or other variable geometry arrangement adapted to control the velocity of exhaust fluid impinging on the turbine wheel 128.

[25] The compressor 124 includes a compressor wheel 134 carried by the shaft 130. Thus, rotation of the shaft 130 by the turbine wheel 128 in turn may cause rotation of the compressor wheel 134.

[26] The first turbocharger 120 may include a compressed air duct 138 for receiving compressed air from the second turbocharger 140 and an air outlet line 152 for receiving compressed air from the compressor 124 and supplying the compressed air to the intake manifold 114 of the engine 110. The first turbocharger 120 may also include an exhaust duct 139 for receiving exhaust fluid from the turbine 122 and supplying the exhaust fluid to the second turbocharger 140.

[27] The second turbocharger 140 may include a turbine 142 and a compressor 144. The turbine 142 may be fluidly connected to the exhaust duct 139. The turbine 142 may include a turbine wheel 146 carried by a shaft 148, which in turn may be rotatably carried by the housing 132. The compressor 144 may include a compressor wheel 150 carried by the shaft 148. Thus, rotation of the shaft 148 by the turbine wheel 146 may in turn cause rotation of the compressor wheel 150.

- [28] The second turbocharger 140 may include an air intake line 136 providing fluid communication between the atmosphere and the compressor 144. The second turbocharger 140 may also supply compressed air to the first turbocharger 120 via the compressed air duct 138. The second turbocharger 140 may include an exhaust outlet 154 for receiving exhaust fluid from the turbine 142 and providing fluid communication with the atmosphere. In an embodiment, the first turbocharger 120 and second turbocharger 140 may be sized to provide substantially similar compression ratios. For example, the first turbocharger 120 and second turbocharger 140 may both provide compression ratios of between 2 to 1 and 3 to 1, resulting in a system compression ratio of at least 4:1 with respect to atmospheric pressure. Alternatively, the second turbocharger 140 may provide a compression ratio of 3 to 1 and the first turbocharger 120 may provide a compression ratio of 1.5 to 1, resulting in a system compression ratio of 4.5 to 1 with respect to atmospheric pressure.
- [29] The air supply system 100 may include an air cooler 156, for example, an aftercooler, between the compressor 124 and the intake manifold 114. The air cooler 156 may extract heat from the air to lower the intake manifold temperature and increase the air density. Optionally, the air supply system 100 may include an additional air cooler 158, for example, an intercooler, between the compressor 144 of the second turbocharger 140 and the compressor 124 of the first turbocharger 120. Alternatively, the air supply system 100 may optionally include an additional air cooler (not shown) between the air cooler 156 and the intake manifold 114. The optional additional air cooler may further reduce the intake manifold temperature.
- [30] Referring now to FIG. 2, a cylinder head 211 may be connected with the engine block 111. Each cylinder 112 in the cylinder head 211 may be provided with a fuel supply system 202. The fuel supply system 202 may include a fuel port 204 opening to a combustion chamber 206 within the cylinder 112.

The fuel supply system 202 may inject fuel, for example, diesel fuel, directly into the combustion chamber 206.

[31] The cylinder 112 may contain a piston 212 slidably movable in the cylinder. A crankshaft 213 may be rotatably disposed within the engine block 111. A connecting rod 215 may couple the piston 212 to the crankshaft 213 so that sliding motion of the piston 212 within the cylinder 112 results in rotation of the crankshaft 213. Similarly, rotation of the crankshaft 213 results in a sliding motion of the piston 212. For example, an uppermost position of the piston 212 in the cylinder 112 corresponds to a top dead center position of the crankshaft 213, and a lowermost position of the piston 212 in the cylinder 112 corresponds to a bottom dead center position of the crankshaft 213.

[32] As one skilled in the art will recognize, the piston 212 in a conventional, four-stroke engine cycle reciprocates between the uppermost position and the lowermost position during a combustion (or expansion) stroke, an exhaust stroke, and intake stroke, and a compression stroke. Meanwhile, the crankshaft 213 rotates from the top dead center position to the bottom dead center position during the combustion stroke, from the bottom dead center to the top dead center during the exhaust stroke, from top dead center to bottom dead center during the intake stroke, and from bottom dead center to top dead center during the compression stroke. Then, the four-stroke cycle begins again. Each piston stroke correlates to about 180° of crankshaft rotation, or crank angle. Thus, the combustion stroke may begin at about 0° crank angle, the exhaust stroke at about 180°, the intake stroke at about 360°, and the compression stroke at about 540°.

[33] The cylinder 112 may include at least one intake port 208 and at least one exhaust port 210, each opening to the combustion chamber 206. The intake port 208 may be opened and closed by an intake valve assembly 214, and the exhaust port 210 may be opened and closed by an exhaust valve assembly 216. The intake valve assembly 214 may include, for example, an intake valve 218 having a head 220 at a first end 222, with the head 220 being sized and

arranged to selectively close the intake port 208. The second end 224 of the intake valve 218 may be connected to a rocker arm 226 or any other conventional valve-actuating mechanism. The intake valve 218 may be movable between a first position permitting flow from the intake manifold 114 to enter the combustion cylinder 112 and a second position substantially blocking flow from the intake manifold 114 to the combustion cylinder 112. A spring 228 may be disposed about the intake valve 218 to bias the intake valve 218 to the second, closed position.

[34] A camshaft 232 carrying a cam 234 with one or more lobes 236 may be arranged to operate the intake valve assembly 214 cyclically based on the configuration of the cam 234, the lobes 236, and the rotation of the camshaft 232 to achieve a desired intake valve timing. The exhaust valve assembly 216 may be configured in a manner similar to the intake valve assembly 214 and may be operated by one of the lobes 236 of the cam 234. In an embodiment, the intake lobe 236 may be configured to operate the intake valve 218 in a conventional Otto or diesel cycle, whereby the intake valve 218 moves to the second position from between about 10° before bottom dead center of the intake stroke and about 10° after bottom dead center of the compression stroke. Alternatively, the intake valve assembly 214 and/or the exhaust valve assembly 216 may be operated hydraulically, pneumatically, electronically, or by any combination of mechanics, hydraulics, pneumatics, and/or electronics.

[35] The intake valve assembly 214 may include a variable intake valve closing mechanism 238 structured and arranged to selectively interrupt cyclical movement of and extend the closing timing of the intake valve 218. The variable intake valve closing mechanism 238 may be operated hydraulically, pneumatically, electronically, mechanically, or any combination thereof. For example, the variable intake valve closing mechanism 238 may be selectively operated to supply hydraulic fluid, for example, at a low pressure or a high pressure, in a manner to resist closing of the intake valve 218 by the bias of the

spring 228. That is, after the intake valve 218 is lifted, i.e., opened, by the cam 234, and when the cam 234 is no longer holding the intake valve 218 open, the hydraulic fluid may hold the intake valve 218 open for a desired period. The desired period may change depending on the desired performance of the engine 110. Thus, the variable intake valve closing mechanism 238 enables the engine 110 to operate under a conventional Otto or diesel cycle or under a variable late-closing Miller cycle.

[36] As shown in FIG. 4, the intake valve 218 may begin to open at about 360° crank angle, that is, when the crankshaft 213 is at or near a top dead center position of an intake stroke 406. The closing of the intake valve 218 may be selectively varied from about 540° crank angle, that is, when the crank shaft is at or near a bottom dead center position of a compression stroke 407, to about 650° crank angle, that is, about 70° before top center of the combustion stroke 508. Thus, the intake valve 218 may be held open for a majority portion of the compression stroke 407, that is, for the first half of the compression stroke 407 and a portion of the second half of the compression stroke 407.

[37] The fuel supply system 202 may include a fuel injector assembly 240, for example, a mechanically-actuated, electronically-controlled unit injector, in fluid communication with a common fuel rail 242. Alternatively, the fuel injector assembly 240 may be any common rail type injector and may be actuated and/or operated hydraulically, mechanically, electrically, piezo-electrically, or any combination thereof. The common fuel rail 242 provides fuel to the fuel injector assembly 240 associated with each cylinder 112. The fuel injector assembly 240 may inject or otherwise spray fuel into the cylinder 112 via the fuel port 204 in accordance with a desired timing.

[38] A controller 244 may be electrically connected to the variable intake valve closing mechanism 238 and/or the fuel injector assembly 240. The controller 244 may be configured to control operation of the variable intake valve closing mechanism 238 and/or the fuel injector assembly 240 based on one or

more engine conditions, for example, engine speed, load, pressure, and/or temperature in order to achieve a desired engine performance. It should be appreciated that the functions of the controller 244 may be performed by a single controller or by a plurality of controllers. Similarly, spark timing in a natural gas engine may provide a similar function to fuel injector timing of a compression ignition engine.

[39] Referring now to FIG. 3, each fuel injector assembly 240 may be associated with an injector rocker arm 250 pivotally coupled to a rocker shaft 252. Each fuel injector assembly 240 may include an injector body 254, a solenoid 256, a plunger assembly 258, and an injector tip assembly 260. A first end 262 of the injector rocker arm 250 may be operatively coupled to the plunger assembly 258. The plunger assembly 258 may be biased by a spring 259 toward the first end 262 of the injector rocker arm 250 in the general direction of arrow 296.

[40] A second end 264 of the injector rocker arm 250 may be operatively coupled to a camshaft 266. More specifically, the camshaft 266 may include a cam lobe 267 having a first bump 268 and a second bump 270. The camshafts 232, 266 and their respective lobes 236, 267 may be combined into a single camshaft (not shown) if desired. The bumps 268, 270 may be moved into and out of contact with the second end 264 of the injector rocker arm 250 during rotation of the camshaft 266. The bumps 268, 270 may be structured and arranged such that the second bump 270 may provide a pilot injection of fuel at a predetermined crank angle before the first bump 268 provides a main injection of fuel. It should be appreciated that the cam lobe 267 may have only a first bump 268 that injects all of the fuel per cycle.

[41] When one of the bumps 268, 270 is rotated into contact with the injector rocker arm 250, the second end 264 of the injector rocker arm 250 is urged in the general direction of arrow 296. As the second end 264 is urged in the general direction of arrow 296, the rocker arm 250 pivots about the rocker

shaft 252 thereby causing the first end 262 to be urged in the general direction of arrow 298. The force exerted on the second end 264 by the bumps 268, 270 is greater in magnitude than the bias generated by the spring 259, thereby causing the plunger assembly 258 to be likewise urged in the general direction of arrow 298. When the camshaft 266 is rotated beyond the maximum height of the bumps 268, 270, the bias of the spring 259 urges the plunger assembly 258 in the general direction of arrow 296. As the plunger assembly 258 is urged in the general direction of arrow 296, the first end 262 of the injector rocker arm 250 is likewise urged in the general direction of arrow 296, which causes the injector rocker arm 250 to pivot about the rocker shaft 252 thereby causing the second end 264 to be urged in the general direction of arrow 298.

[42] The injector body 254 defines a fuel port 272. Fuel, such as diesel fuel, may be drawn or otherwise aspirated into the fuel port 272 from the fuel rail 242 when the plunger assembly 258 is moved in the general direction of arrow 296. The fuel port 272 is in fluid communication with a fuel valve 274 via a first fuel channel 276. The fuel valve 274 is, in turn, in fluid communication with a plunger chamber 278 via a second fuel channel 280.

[43] The solenoid 256 may be electrically coupled to the controller 244 and mechanically coupled to the fuel valve 274. Actuation of the solenoid 256 by a signal from the controller 244 may cause the fuel valve 274 to be switched from an open position to a closed position. When the fuel valve 274 is positioned in its open position, fuel may advance from the fuel port 272 to the plunger chamber 278, and vice versa. However, when the fuel valve 274 is positioned in its closed position, the fuel port 272 is isolated from the plunger chamber 278.

[44] The injector tip assembly 260 may include a check valve assembly 282. Fuel may be advanced from the plunger chamber 278, through an inlet orifice 284, a third fuel channel 286, an outlet orifice 288, and into the cylinder 112 of the engine 110.

[45] Thus, it should be appreciated that when one of the bumps 268, 270 is not in contact with the injector rocker arm 16, the plunger assembly 258 is urged in the general direction of arrow 296 by the spring 259 thereby causing fuel to be drawn into the fuel port 272 which in turn fills the plunger chamber 278 with fuel. As the camshaft 266 is further rotated, one of the bumps 268, 270 is moved into contact with the rocker arm 250, thereby causing the plunger assembly 258 to be urged in the general direction of arrow 298. If the controller 244 is not generating an injection signal, the fuel valve 274 remains in its open position, thereby causing the fuel which is in the plunger chamber 278 to be displaced by the plunger assembly 258 through the fuel port 272. However, if the controller 244 is generating an injection signal, the fuel valve 274 is positioned in its closed position thereby isolating the plunger chamber 278 from the fuel port 272. As the plunger assembly 258 continues to be urged in the general direction of arrow 298 by the camshaft 266, fluid pressure within the fuel injector assembly 240 increases. At a predetermined pressure magnitude, for example, at about 5500 psi (38 MPa), fuel is injected into the cylinder 112. Fuel will continue to be injected into the cylinder 112 until the controller 244 signals the solenoid 256 to return the fuel valve 274 to its open position.

[46] As shown in the exemplary graph of FIG. 5, the pilot injection of fuel may commence when the crankshaft 213 is at about 675° crank angle, that is, about 45° before top dead center of the compression stroke 407. The main injection of fuel may occur when the crankshaft 213 is at about 710° crank angle, that is, about 10° before top dead center of the compression stroke 407 and about 45° after commencement of the pilot injection. Generally, the pilot injection may commence when the crankshaft 213 is about 40-50° before top dead center of the compression stroke 407 and may last for about 10-15° crankshaft rotation. The main injection may commence when the crankshaft 213 is between about 10° before top dead center of the compression stroke 407 and about 12° after top dead

center of the combustion stroke 508. The main injection may last for about 20-45° crankshaft rotation.

[47] FIG. 6 is a combination diagrammatic and schematic illustration of a second exemplary air supply system 300 for the internal combustion engine 110. The air supply system 300 may include a turbocharger 320, for example, a high-efficiency turbocharger capable of producing at least about a 4 to 1 compression ratio with respect to atmospheric pressure. The turbocharger 320 may include a turbine 322 and a compressor 324. The turbine 322 may be fluidly connected to the exhaust manifold 116 via an exhaust duct 326. The turbine 322 may include a turbine wheel 328 carried by a shaft 330, which in turn may be rotatably carried by a housing 332, for example, a single-part or multi-part housing. The fluid flow path from the exhaust manifold 116 to the turbine 322 may include a variable nozzle (not shown), which may control the velocity of exhaust fluid impinging on the turbine wheel 328.

[48] The compressor 324 may include a compressor wheel 334 carried by the shaft 330. Thus, rotation of the shaft 330 by the turbine wheel 328 in turn may cause rotation of the compressor wheel 334. The turbocharger 320 may include an air inlet 336 providing fluid communication between the atmosphere and the compressor 324 and an air outlet 352 for supplying compressed air to the intake manifold 114 of the engine 110. The turbocharger 320 may also include an exhaust outlet 354 for receiving exhaust fluid from the turbine 322 and providing fluid communication with the atmosphere.

[49] The air supply system 300 may include an air cooler 356 between the compressor 324 and the intake manifold 114. Optionally, the air supply system 300 may include an additional air cooler (not shown) between the air cooler 356 and the intake manifold 114.

[50] FIG. 7 is a combination diagrammatic and schematic illustration of a third exemplary air supply system 400 for the internal combustion engine 110. The air supply system 400 may include a turbocharger 420, for example, a

turbocharger 420 having a turbine 422 and two compressors 424, 444. The turbine 422 may be fluidly connected to the exhaust manifold 116 via an inlet duct 426. The turbine 422 may include a turbine wheel 428 carried by a shaft 430, which in turn may be rotatably carried by a housing 432, for example, a single-part or multi-part housing. The fluid flow path from the exhaust manifold 116 to the turbine 422 may include a variable nozzle (not shown), which may control the velocity of exhaust fluid impinging on the turbine wheel 428.

[51] The first compressor 424 may include a compressor wheel 434 carried by the shaft 430, and the second compressor 444 may include a compressor wheel 450 carried by the shaft 430. Thus, rotation of the shaft 430 by the turbine wheel 428 in turn may cause rotation of the first and second compressor wheels 434, 450. The first and second compressors 424, 444 may provide first and second stages of pressurization, respectively.

[52] The turbocharger 420 may include an air intake line 436 providing fluid communication between the atmosphere and the first compressor 424 and a compressed air duct 438 for receiving compressed air from the first compressor 424 and supplying the compressed air to the second compressor 444. The turbocharger 420 may include an air outlet line 452 for supplying compressed air from the second compressor 444 to the intake manifold 114 of the engine 110. The turbocharger 420 may also include an exhaust outlet 454 for receiving exhaust fluid from the turbine 422 and providing fluid communication with the atmosphere.

[53] For example, the first compressor 424 and second compressor 444 may both provide compression ratios of between 2 to 1 and 3 to 1, resulting in a system compression ratio of at least 4:1 with respect to atmospheric pressure. Alternatively, the second compressor 444 may provide a compression ratio of 3 to 1 and the first compressor 424 may provide a compression ratio of 1.5 to 1, resulting in a system compression ratio of 4.5 to 1 with respect to atmospheric pressure.

- [54] The air supply system 400 may include an air cooler 456 between the compressor 424 and the intake manifold 114. Optionally, the air supply system 400 may include an additional air cooler 458 between the first compressor 424 and the second compressor 444 of the turbocharger 420. Alternatively, the air supply system 400 may optionally include an additional air cooler (not shown) between the air cooler 456 and the intake manifold 114.

Industrial Applicability

- [55] During use, the internal combustion engine 110 operates in a known manner using, for example, the diesel principle of operation. Referring to the exemplary air supply system shown in FIG. 1, exhaust gas from the internal combustion engine 110 is transported from the exhaust manifold 116 through the inlet duct 126 and impinges on and causes rotation of the turbine wheel 128. The turbine wheel 128 is coupled with the shaft 130, which in turn carries the compressor wheel 134. The rotational speed of the compressor wheel 134 thus corresponds to the rotational speed of the shaft 130.
- [56] The exemplary fuel supply system 200 and cylinder 112 shown in FIG. 2 may be used with each of the exemplary air supply systems 100, 300, 400. Compressed air is supplied to the combustion chamber 206 via the intake port 208, and exhaust air exits the combustion chamber 206 via the exhaust port 210. The intake valve assembly 214 and the exhaust valve assembly 216 may be controllably operated to direct airflow into and out of the combustion chamber 206.
- [57] In a conventional Otto or diesel cycle mode, the intake valve 218 moves from the second position to the first position in a cyclical fashion to allow compressed air to enter the combustion chamber 206 of the cylinder 112 at near top center of the intake stroke 406 (about 360° crank angle), as shown in FIG. 4. At near bottom dead center of the compression stroke (about 540° crank angle), the intake valve 218 moves from the first position to the second position to block additional air from entering the combustion chamber 206. Fuel may then be

injector from the fuel injector assembly 240 at near top dead center of the compression stroke (about 720° crank angle).

[58] In a conventional Miller cycle engine, the conventional Otto or diesel cycle is modified by moving the intake valve 218 from the first position to the second position at either some predetermined time before bottom dead center of the intake stroke 406 (i.e., before 540° crank angle) or some predetermined time after bottom dead center of the compression stroke 407 (i.e., after 540° crank angle). In a conventional late-closing Miller cycle, the intake valve 218 is moved from the first position to the second position during a first portion of the first half of the compression stroke 407.

[59] The variable intake valve closing mechanism 238 enables the engine 110 to be operated in both a late-closing Miller cycle and a conventional Otto or diesel cycle. Further, injecting a substantial portion of fuel after top dead center of the combustion stroke 508, as shown in FIG. 5, may reduce NO_x emissions and increase the amount of energy rejected to the exhaust manifold 116 in the form of exhaust fluid. Use of a high-efficiency turbocharger 320, 420 or series turbochargers 120, 140 may enable recapture of at least a portion of the rejected energy from the exhaust. The rejected energy may be converted into increased air pressures delivered to the intake manifold 114, which may increase the energy pushing the piston 212 against the crankshaft 213 to produce useable work. In addition, delaying movement of the intake valve 218 from the first position to the second position may reduce the compression temperature in the combustion chamber 206. The reduced compression temperature may further reduce NO_x emissions.

[60] The controller 244 may operate the variable intake valve closing mechanism 238 to vary the timing of the intake valve assembly 214 to achieve desired engine performance based on one or more engine conditions, for example, engine speed, engine load, engine temperature, boost, and/or manifold intake temperature. The variable intake valve closing mechanism 238 may also

allow more precise control of the air/fuel ratio. By delaying closing of the intake valve assembly 214, the controller 244 may control the cylinder pressure during the compression stroke of the piston 212. For example, late closing of the intake valve reduces the compression work that the piston 212 must perform without compromising cylinder pressure and while maintaining a standard expansion ratio and a suitable air/fuel ratio.

[61] The high pressure air provided by the exemplary air supply systems 100, 300, 400 may provide extra boost on the induction stroke of the piston 212. The high pressure may also enable the intake valve assembly 214 to be closed even later than in a conventional Miller cycle engine. In the present invention, the intake valve assembly 214 may remain open until the second half of the compression stroke of the piston 212, for example, as late as about 80° to 70° before top dead center (BTDC). While the intake valve assembly 214 is open, air may flow between the chamber 206 and the intake manifold 114. Thus, the cylinder 112 experiences less of a temperature rise in the chamber 206 during the compression stroke of the piston 212.

[62] Since the closing of the intake valve assembly 214 may be delayed, the timing of the fuel supply system may also be retarded. For example, the controller 244 may controllably operate the fuel injector assembly 240 to supply fuel to the combustion chamber 206 after the intake valve assembly 214 is closed. For example, the fuel injector assembly 240 may be controlled to supply a pilot injection of fuel contemporaneous with or slightly after the intake valve assembly 214 is closed and to supply a main injection of fuel contemporaneous with or slightly before combustion temperature is reached in the chamber 206. As a result, a significant amount of exhaust energy may be available for recirculation by the air supply system 100, 300, 400, which may efficiently extract additional work from the exhaust energy.

[63] Referring to the exemplary air supply system 100 of FIG. 1, the second turbocharger 140 may extract otherwise wasted energy from the exhaust

stream of the first turbocharger 120 to turn the compressor wheel 150 of the second turbocharger 140, which is in series with the compressor wheel 134 of the first turbocharger 120. The extra restriction in the exhaust path resulting from the addition of the second turbocharger 140 may raise the back pressure on the piston 212. However, the energy recovery accomplished through the second turbocharger 140 may offset the work consumed by the higher back pressure. For example, the additional pressure achieved by the series turbochargers 120, 140 may do work on the piston 212 during the induction stroke of the combustion cycle. Further, the added pressure on the cylinder resulting from the second turbocharger 140 may be controlled and/or relieved by using the late intake valve closing. Thus, the series turbochargers 120, 140 may provide fuel efficiency via the air supply system 100, and not simply more power

[64] It should be appreciated that the air cooler 156, 356, 456 preceding the intake manifold 114 may extract heat from the air to lower the inlet manifold temperature, while maintaining the denseness of the pressurized air. The optional additional air cooler between compressors or after the air cooler 156, 356, 456 may further reduce the inlet manifold temperature, but may lower the work potential of the pressurized air. The lower inlet manifold temperature may reduce the NO_x emissions.

[65] An air and fuel supply system for an internal combustion engine in accordance with the exemplary embodiments of the invention may extract additional work from the engine's exhaust. The system may also achieve fuel efficiency and reduced NO_x emissions, while maintaining work potential and ensuring that the system reliability meets with operator expectations.

[66] It will be apparent to those skilled in the art that various modifications and variations can be made in the disclosed air and fuel supply system for an internal combustion engine without departing from the scope or spirit of the invention. Other embodiments of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the

invention disclosed herein. It is intended that the specification and examples be considered as exemplary only.